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ROBOTIC – COMPUTER ASSISTED IMPLANT SURGERY

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ABSTRACT

Robotic computer-assisted implant placement represents a significant technological advancement in implant dentistry, aiming to improve the accuracy, safety, and predictability of dental implant surgery. This approach integrates cone-beam computed tomography (CBCT), three-dimensional virtual planning software, and robotic guidance systems to facilitate precise, prosthetically driven implant placement based on patient-specific anatomical considerations. Detailed preoperative planning allows the clinician to determine the optimal implant position, angulation, and depth while identifying potential anatomical risks. During the surgical procedure, robotic systems provide real-time guidance and haptic feedback, assisting the operator in maintaining the planned implant trajectory and minimizing deviations from the preoperative plan. Compared with conventional freehand implant placement, robotic-assisted techniques have demonstrated superior accuracy, improved consistency, and reduced risk of damage to adjacent vital structures such as the inferior alveolar nerve and maxillary sinus. These improvements may contribute to enhanced primary implant stability, improved prosthetic outcomes, and increased long-term implant success rates. However, the widespread adoption of robotic technology is currently limited by factors such as high initial costs, limited availability of equipment, and the learning curve associated with its clinical implementation. Despite these challenges, robotic computer-assisted implant placement shows considerable promise in advancing modern implantology. Further well-designed clinical trials and long-term studies are required to assess its clinical effectiveness, cost-benefit ratio, and potential integration into routine dental practice.

KEYWORDS: Robotic implant surgery; Computer-assisted implant surgery; Dental implants; Dynamic navigation; Static guided surgery; Artificial intelligence.

INTRODUCTION

Robotic systems have emerged as an advanced approach in dental implantology, offering enhanced precision, improved safety, and greater predictability in implant placement.[1] This ensures accurate three-dimensional implant positioning. (3D) virtual planning.[2] Achieving optimal implant placement, which is influenced by factors such as bone quality. quantity, anatomical structures, prosthetic design, and patient preferences.[1,3] Such limitations can increase the risk of implant misplacement, nerve injury, sinus involvement, postoperative infection, implant failure, and aesthetic complications.[2,3] To overcome these limitations.

Current robotic technologies are classified into static-guided and dynamic-guided systems.[13] Static-guided surgery utilises a prefabricated template, secured to the patient's jaw, to precisely guide the drilling trajectory. Dynamic-guided surgery, a computerised navigation system, continuously monitors the drill and jaw orientation, providing real-time feedback on a display.[1] The ultimate goal is to minimise invasiveness and intraoperative stress, enhance patient satisfaction, and improve long-term clinical outcomes.[1,2]

HISTORY OF ROBOTIC SURGERY

This first robotic system was developed by Dr. Stefan Hadfield from the University Hospital of Heidelberg, Germany, developed the first robotic system and performed the initial proof-of-concept dental implant in 2002, involving mock drillings on a phantom mandible with 16 trials and 48 precise placements.[5]

Key Milestones

- **2002**: Hadfield et al. performed the first robot-guided dental implant mock surgery. Germany using a system with 70 cm scope for preoperative planning and handpiece guidance.[14]
- **2017**: World's first autonomous robotic implant surgery in Xi'an, China, by a team from Beihang University and Fourth Military Medical University (led by Prof. Zhao Yimin), placing two 3D-printed implants with 0.2-0.3 mm accuracy in under an hour using CT fusion.[15]
- **2022**: Yomi gains FDA clearance for YomiPlan Go workflow and bone reduction, enhancing planning and flapless procedures.[16]
- **2025**: Yomi exceeds 47,000 implants; reviews report average deviations of 0.76 mm, with AI integration for prosthodontic full-arch restorations.[17]

INDICATIONS

- Adults with dentition defects who have become either fully or partially edentulous, aged 18 to 70.[18]
- Mouth opening ≥35 mm, good oral hygiene, and good general health.[19]
- Sufficient bone support and at least two adjacent teeth for marker fixation.[21]
- Flapless single or multiple implants are suitable in cases without severe bone defects.[21]
- Complex scenarios like full-arch rehabilitation (e.g., All-on-4), sinus lifts, or zygomatic implants.[21]
- A controlled medical condition, adequate bone, or willingness to be treated bone grafting.[21]

CONTRAINDICATION

- Uncontrolled systemic diseases, especially diabetes, hypertension, and bleeding disorders, and pregnancy.[21]
- Alcoholism, resin acrylic asthma or allergies, or heavy smoking (≥10 cigarettes per day).[20]
- Inadequate keratinised tissue (<2 mm post-flapless) and general implant contraindications.[20]
- A inadequate mouth opening, restricted inter-arch space, or anatomical limitations (as well as poor hard/soft tissue).[21]

LIMITATIONS

- Accessibility is hampered by high equipment acquisition, maintenance, and training costs, especially for rural patients and smaller clinics.[19]
- Depending on the surgeon's skill and knowledge, the robot assists, but for optimal results, clinical judgment is still necessary.[19]
- Robotic systems such as Yomi or Remebot are not available at all practices.[20]
- Marker fixation suggests enough teeth and bone; severe atrophy or edentulous cases without support cannot be sufficient.[21]
- Marker placement and surgery are impaired in restricted mouth opening (<35 mm) or inter-arch space.

COMPUTER-ASSISTED ROBOTIC DENTAL IMPLANT

Dental implants that achieve osseointegration are widely recognized as the optimal approach for replacing missing teeth.[1] The success of implant surgery on the accurate placement of the implant, considering factors such as depth, angle, and location within the bone.[1,2] To improve the precision of implant placement and minimize errors, surgeons have utilized navigation systems and template guidance.[4,5]

Dental implant surgery has made use of a variety of navigation systems, such as Landmar X, Navident, Vector Vision, and the Aq Navi Surgical Navigation System.[5] While the Landmark X system employs active infrared tracking, the the Navident system uses visual surgical navigation. Improved stability, higher flexibility, sustained precision, and enhanced efficiency are just a few advantages of robotic surgery.[8] Surgical robotics consists of two main parts: image guidance and a portable robotic device. Robotic computer-assisted implant surgery uses a mix of digital scan and CBCT data to guide the execution of a pre-planned implant position. By ensuring precise control over angulation, depth, and placement, the robot increases precisionand reduces the risk of harm to important structures. Despite its great precision and repeatability, its use is restricted by its exorbitant cost, lengthy setup time, and training requirements.[3]

ROBOT-ASSISTED MANUFACTURED SURGICAL TEMPLATE

The surgical guiding template is a dependable method to aid in diagnostics and guarantee a precise placement of the dental implant.[22] The manufacturing design and method—such as computed tomography-generated static guides, cast-based surgical guides, and vacuum-formed templates—determines the mistake associated with surgical templates.[23]

A high-precision, patient-specific guide created using robot-controlled fabrication based on digital implant planning is known as a robot-assisted made surgical template.[24] It improves precision and predictability in implant placement by offering precise control over drill angulation and depth.[24] High cost, the requirement for precise data collection, and appropriate seating are some of its drawbacks.[24]

COMMERCIAL ROBOTIC SYSTEMS AND THEIR MANUFACTURERS

Several commercial robotic systems exist for dental implant surgery, primarily from US and Chinese manufacturers, with Yomi leading in FDA-cleared adoption. These systems integrate imaging, planning, and haptic guidance for precise osteotomy and placement.[10,11]

Additional Innovators

- Zimmer Biomet (USA): Leading patent filer in robotic dental tools.
- X-Nav Technologies (USA): Optical tracking-integrated systems.
- Navigate Surgical Technologies (USA): Contributes to robotics patents.

These systems address limitations in freehand surgery, though availability varies by region and cost.

ROBOTIC IMPLANT SURGERY WORKFLOW

Robotic dental implant workflows follow a standardized sequence from digital planning to precise execution, integrating CBCT imaging, software simulation, and haptic/robotic guidance for sub-millimeter accuracy.[12]

Preoperative Planning

CBCT scans and intraoral impressions create 3D models for virtual implant positioning, angulation, and depth using software like YomiPlan.[25] Clinicians review the plan for prosthetic outcomes, anatomic risks, and patient consent, often with AI enhancements for full-arch cases.[25]

Intraoperative Steps

1. Administer anesthesia and position patient.[25]
2. Perform registration via fiducials, optical markers, or bone tracking to align digital plan with anatomy.[25]
3. Perform registration via fiducials, optical markers, or bone tracking to align digital plan with anatomy.[25]
4. Drill osteotomy with haptic feedback—system resists deviations in trajectory/depth (Yomi locks handpiece; Remebot uses optical guidance). [25]
5. Insert implant under guidance; verify with postoperative CBCT.[25]

Postoperative Phase

1. Suture if needed, attach healing abutment, and monitor integration; digital records enable prosthodontic continuity. Total time reduces by up to 30-50% versus freehand, with flapless options for soft tissue preservation. [26]

PRACTICING ROBOTIC IMPLANTOLOGY

The practicing surgeon took into account the following, the robotic arms could be controlled efficiently.[6] The surgeon should first understand all aspects of carrying out the surgical technique in the robotic system.[3] This means that while practicing bimanual wrist manipulation on the robotic system, the surgeon should also think about learning how to control the stereoscopic camera, activate energy sources, adjust the robotic arm position.[2] The abilities to operate the robotic console correctly and the psychomotor abilities for the robotic surgical system.[7] In addition to the expertise of the practicing surgeon, a competent team of anesthesiologists, nurses, and assistants is necessary for a successful robot-assisted surgical procedure.[2] The surgeon is physically segregated from the surgical field, completely occupied, and secluded from the rest of the surgical team during the process.[3] Effective teamwork and communication should be taken into account in simulation-based team-based learning to reduce procedure time and guarantee ideal team dynamics.[5] During dynamic navigation-guided implant placement, the surgeon must monitor the drill and implant positions displayed on the screen.

ACCURACY OF IMAGE ACQUISITION

The appropriate implant planning requires precise measurements of anatomic features and accurate evaluation of bone architecture.[1] The slice thickness and the impact of potential artifacts determine the quality of CT data.[25] The spatial precision and accuracy of measurements of defined anatomical structures increase with decreasing slice thickness and voxel size, 46–48 Geometric distortions and inaccurate data collection may result from dental restoration movement and metallic artifacts.[7]

Accuracy of image acquisition depends on **resolution and calibration** of CBCT/intraoral scans, **absence of motion artifacts**, and **proper alignment during data capture**, as any distortion directly affects **implant planning precision**.[24,25]

ACCURACY OF REGISTRATION

Accurate registration ensures faithful translation of the virtual surgical plan to the operative site.[25] We refer to this as the image-to-physical conversion. The coordinates in the imaging space and their corresponding positions in the patient's physical space) must be mapped 1-to-1; Points in the imaging and physical spaces that correspond to the same anatomical location must be accurately mapped.[20] Point-based (fiducial) registration is the foundation used in navigation systems for image-guided bur tracking.[21] It is impossible to describe anatomic landmarks precisely

According to Marmulla and colleagues 55, markers may fall between two CT slices during data gathering. This could lead to false target measurements, improper marker correlation on the CT data, *and the spatial rotation of the registered dataset relative to the anatomical structures*.[22]

COMPUTER-ASSISTED IMPLANT SURGERY USING DYNAMIC NAVIGATION

Both active and passive dynamic navigation systems were registered and calibrated before use.[24] The calibration was done in to locate and monitor the implant handpiece in real time and the mandibular model that was worn during implant surgery with the reference plate.[24,25] The reference plate, and infrared optical tracker must all form a clear, straight route during the calibration procedure.[23]

In order to complete the spatial registration of the implant handpiece and the reference plate, the dynamic navigation system recorded and transformed their spatial coordinates.[23] It is helpful in locations with restricted access, offers constant visual input, and enhances depth control and angulation accuracy.[23] However, it is more expensive and requires more training, as well as operator expertise and accurate calibration.[22]

GUIDED COMPUTER-ASSISTED IMPLANT SURGERY ENHANCES PERI-IMPLANT SOFT TISSUE OUTCOMES

There was no significant differences were observed in peri-implant tissue health parameters, including bleeding on probing and probing depths, for the implants. According to a recent comparative cross-sectional investigation.[24] This is positioned in the esthetic zone with guided CAIS four years after loading on average.[25]

By enabling prosthetically driven implant positioning, protecting keratinized mucosa, minimizing flap elevation, and minimizing tissue trauma, guided computer-assisted implant surgery (CAIS) promotes stable soft tissue contours and better long-term peri-implant health.[24,25]

HUMAN FACTORS IN ROBOTIC IMPLANT SURGERY

All the imaging, planning, and transmission problems are the result of human error. As a result, each stage needs to be handled carefully.[24] Comprehensive registration placement devices, immobile CT data collection, accurate planning, registration accuracy verification, and ongoing focus on a steady and accurate fit of the dynamic reference frame or registration template are all necessary.[24,25]

Clinical success depends on the implant surgeon's ability comprehend and apply positional information *displayed on the monitor* during implant o*steotomy preparation*, since Bur tracking is affected by hand tremors and perceptual errors of roughly 0.25 mm and 0.5 degrees 68.[20] One could think that image-guiding would be more beneficial in complicated settings with less anatomic orientation.[25]

It lead to better functional and aesthetic outcomes as well as a potential decrease in the risk of surgery.[22] In the future, technology might connect operator precision with drill speed.[24] When the bur's location and angle are outside of a specific degree of precision, the drill will either automatically stop or slow down before it reaches a crucial anatomical structure.[25]

COST–EFFECTIVENESS OF ROBOTIC IMPLANT DENTISTRY

Compared with traditional implant placement techniques, computer-aided implant surgery is more costly and involves more work, such as CT imaging and registration manufacturing.[21]

Template, as well as intraoperative referencing for bur tracking or image-guided surgical template production.[20] Bur-tracking navigation systems are the most expensive, costing between $60,000 and $200,000 US Because components\ *on both the registration template and the drill* require continuous visual contact with the stereotactic optical tracking system reference and navigation during implant surgery, the procedure is prolonged and necessitates ergonomic implant surgeon's concessions.[21,22]

Automatic and comprehensive electronic documentation of the intervention is another advantage of using computer-aided technology.[23] One benefit is that a variety of craniomaxillofacial treatments (such as image-guided biopsies, foreign body removal, temporomandibular joint arthroscopy, osteotomies, distraction osteogenesis, and tumour surgery) could therefore be a beneficial addition for an organisation.[20,21]

Because intraoperative referencing is not required, image-guided template creation and involves less work than bur tracking.[25]

RECENT ADVANCEMENTS IN ROBOTIC DENTAL IMPLANT SURGERY

AI-powered planning, hybrid tracking systems, and enhanced calibration for sub-millimeter precision.[11]

AI Integration

Neocis unveiled next-generation Yomi updates in November 2025 with AI for prosthodontic full-arch restorations and predictive analytics, reducing deviations to 0.76 mm across 47,000+ cases. AI analyzes CBCT for bone density, optimizing trajectories and minimizing errors.[11,12]

Novel Tracking Systems

2025 studies introduced optical navigation for automatic calibration (1.44 mm platform deviation) and hybrid 5/6-DOF arms (0.8 mm platform, 1.01° angular), outperforming traditional methods in edentulous jaws. Markerless vision-guided systems enable flapless procedures with real-time adjustments.[11]

Clinical Expansions

Trials expanded RAIS to immediate anterior implants, jaw defects, and edentulous patients, showing consistent accuracy independent of site or surgeon experience; future includes VR simulations and autonomous drilling safeguard.[13]

LEGENDS

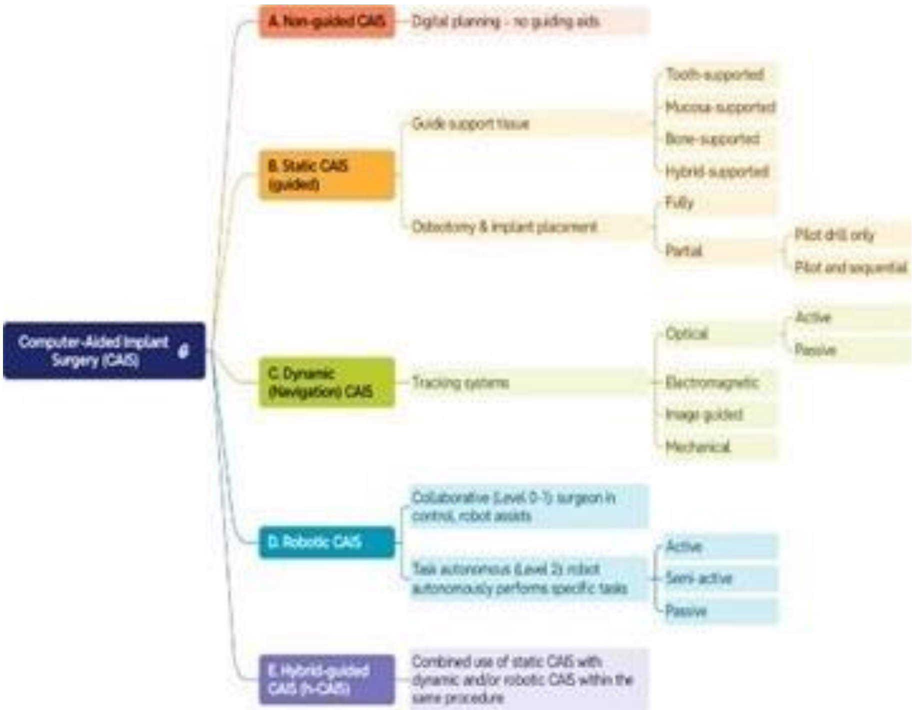

Figure 1: classification of cais techniques in implant dentistry, adapted from garcia et al., 2025. sources: jorba-garcia a., pozzi a., chen z., et al. glossary of computer-assisted implant surgery and related terms, first edition. *clinical & experimental dental research* 2025.

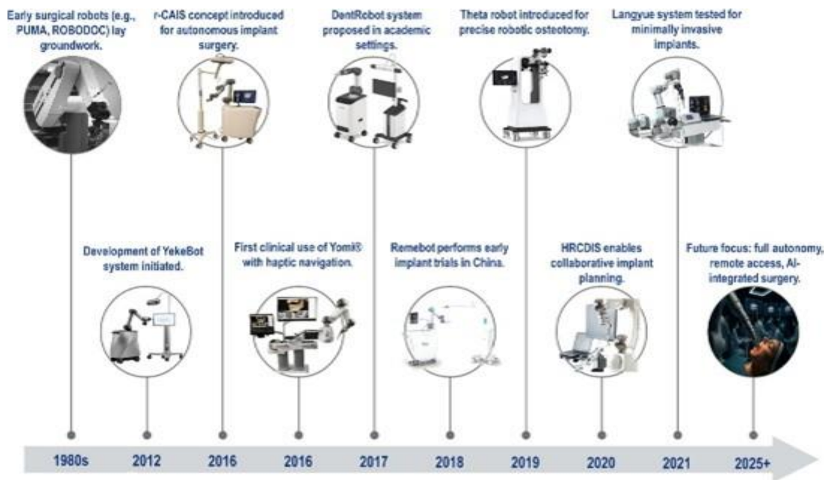

Figure 2; evolution of dental implant robotics: a timeline of key milestones (1980s-2025+) source: tuygunov n, mattheos n, tsoi j, ruzikulova m, osathanon t, samaranayake l. contemporary applications of robotic systems in dental implantology: a review. *int dent j.* 2026;76(1):10933

COMMERCIAL ROBOTIC SYSTEMS AND THEIR MANUFACTURERS.

Sr. No	System	Manufacturer	Key Notes [Sources]
1.	Yomi	Neocis Inc. (USA)	FDA-cleared since 2016; over 47,000 implants placed; AI-enhanced planning.
2.	Remebot	Beijing Ruiyibo Technology (China)	Portable system for neurosurgery and dental implants; clinical trials ongoing.
3.	Yakebot	Yekebot Technology Co. (China)	Autonomous robotic system for edentulous cases; real-time navigation.
4.	sa-RASS	Not specified (research prototype)	Superior accuracy vs. dynamic navigation in studies.

CONCLUSION

The precision of image-guided oral implant systems is determined by cumulative errors from data acquisition to surgery, requiring a safety margin equal to the maximum deviation. Both bur-tracking and template-guided approaches provide comparable accuracy, enabling precise implant placement, though computer-assisted implant surgery involves substantially higher costs than conventional techniques.[24]

Dental implants are thought to be the most common method of restoring lost teeth. According to our research, robotically assisted implant surgery help greatly to implant surgery by guaranteeing accurate implant positioning in the jaw and paying attention to the implant's depth, angle, and location within the bone.[25] Furthermore, since future robotic-surgeon collaboration has the potential to transform implant dentistry, surgeons who practice implants should possess sufficient knowledge and experience in robotic surgery.[25]

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